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Mechanical and Ballistic Properties of Composites of Polypyrrole-Coated S-2 Glass Fabrics

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Abstract

This report presents the results of mechanical and ballistic tests on polyester and polyurethane-based composites of polypyrrole-coated S-2 glass fabrics. The fabrics were obtained from the Milliken Research Corporation, Spartanburg, SC. The data support the proposition that the glass fibers are, at most, slightly damaged by the coating process that requires an acidic solution of pH 1. The mechanical properties of the interface between the glass fibers and the matrix resin are weakened by the presence of the polypyrrole coating in the polyester resin composites. As a consequence, the tensile, compressive, flexure, and short-beam-shear strengths are all lower than comparable composites made with uncoated fabrics. The ballistic properties of the polypyrrole-coated-fabric polyester resin composites are as good or perhaps even slightly better, however, as a result of increased delamination. The tensile strengths of the polypyrrole-coated-fabric polyurethane composites were slightly higher than for similar composites made with uncoated fabrics, although the flexural modulus was not changed. The tensile strength of the polypyrrole-coated fabrics was also measured and found to be about 20% higher than comparable amino-silane-sized fabrics, apparently as a consequence of the increased lubricity of the polypyrrole-coated fibers.

Acknowledgments

Messrs. Timothy O'Shea and David Chandlee (University of Delaware) assisted with the preparation of the vacuum-assisted resin-transfer molding (VARTM) panels from which test specimens were cut. Messrs. Steven Ngyuen, Paul Moy, David Flanagan, and Alan Teets and Mrs. Linda Ghiorse (U.S. Army Research Laboratory [ARL] Polymers Research Branch) helped set up the mechanical tests. Mr. Matthew Burkins and his ballistic range assistants (in the ARL Armor Mechanics Branch) performed the 22-cal. ballistic tests. Mr. William E. Haskell III (currently at the U.S. Army Natick Laboratory) arranged for the thick test panel fabrication and 20-mm fragment ballistic testing. Mr. Jeffery Swab (ARL Metals and Ceramics Research Branch) ran the Weibull analyses on the fabric tensile strength data. Mr. Dana Granville (ARL Composites and Lightweight Structures Branch) and Dr. Steven McKnight (ARL Polymers Research Branch) performed critical reviews of the manuscript. Dr. Hans Kuhn (Milliken Research Corporation) provided much technical insight into conductive polymers and, particularly, their application to textiles.

The assistance of these people is gratefully appreciated.

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1. Introduction

Polypyrrole-coated fabrics have now been available from the Milliken Research Company for a number of years.* In previous research at the U.S. Army Research Laboratory (ARL), these fabrics were found to exhibit interesting dielectric properties when fabricated into composites of thermoset resins [1]. These dielectric properties make such composites interesting for use in a variety of structural applications. A similar analysis of the mechanical and ballistic properties of these composite materials, the focus of the work presented in this report, is also needed if they are to be used for such structural applications.

The polypyrrole coating applied to the fabrics is very thin, far less than a micron thick [2]. The coating is applied by a fabric dyeing process in an aqueous acid bath with a pH of approximately 1. It can be applied to a variety of fabrics including nylon, polyester, Kevlar, quartz, and S-2 glass. S-2 glass fabrics to be coated must be protected from the acid bath by the polymeric sizing that is applied to protect the fibers in handling and to control the mechanical properties of the fiber matrix interface in composites. The polypyrrole coating is made conductive by doping with an aromatic disulphonic acid, so the sizing must continue to protect the glass, even after it is coated and dried. For the Milliken Research Corporation process, amino-silane sizings have been found to be best for protecting the glass in the acid bath and adhering to the polypyrrole. Because the fabrics are immersed in a highly acidic bath and are handled extensively during the coating process, it is possible that the process could decrease the strengths of fibers in the fabric. The handling of the fabrics during the coating process can introduce weft distortion in the fabric and mechanical damage to the fibers. Both can adversely affect the mechanical properties of composites made from these fabrics.

The polypyrrole coating is applied over the sizing on the fabric as an additional layer of material between the glass and the matrix resin. This can have a potentially adverse effect on the mechanical properties of the interface, particularly if the adhesion of the coating to the sized fibers is poor.

* Milliken Research Company, PO Box 1926, Spartanburg, SC 29303.

Previous work at ARL, presented at the December 1994 Materials Research Society meeting [3], did not clearly answer questions of the effects of the polypyrrole coating on mechanical and ballistic properties of polyester resin matrix composites fabricated with these coated fabrics. Since no account of this work has been published, it is presented in this report. In new work, also presented here, the tensile, compressive, and flexure strengths and moduli and the short-beam-shear strength of polyester resin matrix composites of polypyrrole-coated S-2 glass were compared with those of similarly prepared composites of uncoated glass. The tensile strength and flexure modulus of composites of uncoated and polypyrrole-coated S-2 glass in polyurethane resins are also of interest, and the results of these measurements are presented here. Ballistic tests of the polyester composites were also performed using a 22-cal. fragment-simulating projectile. Finally, tensile tests on the uncoated and polypyrrole-coated fabrics were performed in an attempt to separate effects of the coating on the fiber strength from its effects on the mechanical properties of the interface.

A literature search was conducted on composites of polypyrrole-coated fabrics. The only article of interest found was a report on polypyrrole-coated E-glass by Attias et al. [4]. The polypyrrole coating in this work was prepared using a different dopant to obtain a high conductivity. In their work, Attias et al. studied both a commercial amino-silane sizing and a special amino-silane sizing in which the amine was pyrrole. The adherence of their polypyrrole coating to sized fibers was rather poor with the commercial sizing, leading to low interlaminar shear strength in an epoxy composite. The special sizing adhered to the polypyrrole coating quite well, however, and no decrease in interlaminar shear strength was noted in the epoxy matrix composites. No tensile, compressive, or flexure strength data were reported for these composites.

2. Sample Preparation

Most of the fabrics used in this work were type 6781 S-2 glass, an 8.8-oz, 8-harness satin weave, with 58 ends (fibers in the long direction of a roll) and 55 picks (fibers in the direction

across the roll) per inch. These glass fabrics were obtained from JPS Glass* and were sized with JPS's standard 9827 amino-silane sizing. Batches of these fabrics were coated with polypyrrole by Milliken Research Corporation. Uncoated fabrics were also obtained directly from JPS Glass. Some composites were also made with a 6781 fabric with a Volan sizing obtained from Lydall-Manning† in order to have samples with another sizing for comparison. Polypyrrole-coated, 24-oz S-2 glass woven roving fabrics with five picks and five ends per inch with an Owens-Corning‡ type 933 high-temperature sizing were also available. In preliminary experiments, however, these were found to have too much weft distortion that could not be straightened out well enough to provide meaningful mechanical test results. Finally, a quantity of the 24-oz 5 × 5 woven roving with Owens-Corning's type 463 epoxy-based sizing that had been coated to have a sheet resistance of 250 Ω per square was also available. Although the adhesion of the polypyrrole coating to this particular fabric was described by the supplier as not being as good as it could be, it was tested to see how well it would perform in polyester resin-based composites. This fabric was also used in a thick section composite for a special ballistic test.

Previous applications of the polypyrrole-coated fabrics at ARL have been in composites in which the matrix polymer resin was either polyester (Alpha Owens Corning's E-701-3§) or polyurethane (Uniroyal Chemical's Adiprene-L 100, cured with Catur 21**). No evidence of a chemical reaction of these resins with the polypyrrole coating has been detected, and it is also relatively easy to work with the resins. These two resins were therefore selected as a matrix for the mechanical property test samples.

The initial composite panels for mechanical test specimens were fabricated using standard hand lay-up methods with wet resins. This process has some drawbacks that make it poorly suited for preparing mechanical test specimens. First, it is hard to get the resin content truly

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* JPS Glass, PO Box 260, Slater, SC 29683.
† Lydall-Manning, 2800 Turnpike Drive, Hatboro, PA 19040.
‡ Owens-Corning Fiberglas, 2790 Columbus Road, Route 16, Granville, OH 43023-1210.
§ Alpha Owens Corning, 2552 Industrial Drive, Valparaiso, IN 46383-9510.
** Uniroyal Chemical Company, Benson Road, Middlebury, CT 06749.

uniform throughout the panel. This can lead to resin-rich and resin-poor areas in the composite, which can adversely affect the mechanical properties. Similarly, the overall resin content is difficult to control. Also, the process involves handling of wet fabrics, which can lead to significant weft distortion.

In later work, the hand lay-up process was replaced by a vacuum-assisted resin-transfer molding (VARTM) process [4]. This process produces panels with fiber-volume fractions that are as consistent as those obtained by any other method, with the possible exception of matched metal molding, and effectively eliminated fiber-volume fraction as a variable. Since the process used dry fabrics, it is also much easier to control weft distortion in the panels. Care was taken to align the fabrics in the same direction. For the polyester resin-based samples, a 2-ft-wide × 4-ft-long composite panel of 23 layers of polypyrrole-coated type 6781 S-2 glass fabric and 5 plies of uncoated S-2 glass was fabricated using the VARTM method.

This mix of fabrics is a worst-case simulation of how the coated fabrics might actually be used. The fabric plies in the panel were aligned so that the fill direction of the fabrics was the long direction of the panel. Two similar panels were made using uncoated S-2 glass fabrics, one with the JPS Glass amino-silane sizing and the other with a polyester/epoxy-compatible "Volan" sizing. The polyester-based panels were cured 1 hr at 160° F and post-cured 1 hr at 250° F to develop the full mechanical strength of the resin. The panels were kept under vacuum over night as they cooled to room temperature.

The polyurethane matrix composites were also fabricated by the VARTM process. The fabrics and resin were heated to about 140° F to lower the viscosity of the resin and ease its flow into the panels. Ten-ply panels, each 10 in wide × 16 in long, were fabricated, one from a fabric coated to have a 120-Ω-per-square-sheet resistance and one from a uncoated amino-silane-sized fabric. These panels were made side by side in the same vacuum bag to reduce the difference in fiber volume in the samples as much as possible. Two additional panels of similar size were also made side by side in a vacuum bag, one with uncoated fabric and one with a mixture of five plies each of 3,750- and 530-Ω-per-square fabrics. The panels were cured for 1 hr at 250° F and allowed to cool overnight to room temperature while under vacuum.

The initial, pre-1995, mechanical test samples (all with polyester resin) were machined in the ARL shop at Watertown, MA, prior to the move of the ARL Materials Directorate to Aberdeen Proving Ground (APG) that year. All other mechanical test samples were cut from polyester resin-based composite panels made after the move by Dess Machine and Manufacturing.* The long axis of the samples was the warp direction of the fabrics in all cases, except for a few of the earliest samples for which samples were also cut in the orthogonal (fill) direction. Typical samples are shown in Figure 1. For the polyurethane-based panels, mechanical test samples similar to those in Figure 2 were cut using a sharp die in a hydraulic cutting machine.

3. Mechanical Property Tests

3.1 Polyester Matrix Composites. The mechanical tests performed on the polyester matrix composites and American Society for Testing of Materials (ASTM) specifications [5–8] for the tests are shown in Table 1. These are the standard tests for S-2 glass composites required in MIL-PRF-46197A [9].

The tensile strength and modulus of a composite are determined in large part by the strength of the reinforcement materials, although the matrix and interface also play a significant role. As a consequence, the tensile strength and modulus are less affected by variations in the resin content of the composite than the other tests. The flexure, compression, and shear properties are strongly affected by the resin, the fiber concentration, and interface properties. Meaningful comparisons of these properties for samples with coated and uncoated glass are possible only if the percentage of fiber in the samples does not differ greatly from one sample to another. Of the early (pre-1995) samples, only those made with the 24-oz 5 × 5 woven roving with the Owens-Corning type 463 sizing were sufficiently close in fiber content to permit comparison. The results of these tests are shown in Table 2. These samples contained about 51 ±1% glass fiber by volume.

* Dess Machine & Manufacturing, Inc., 5049 North Dupont Highway, Dover, DE 19901.

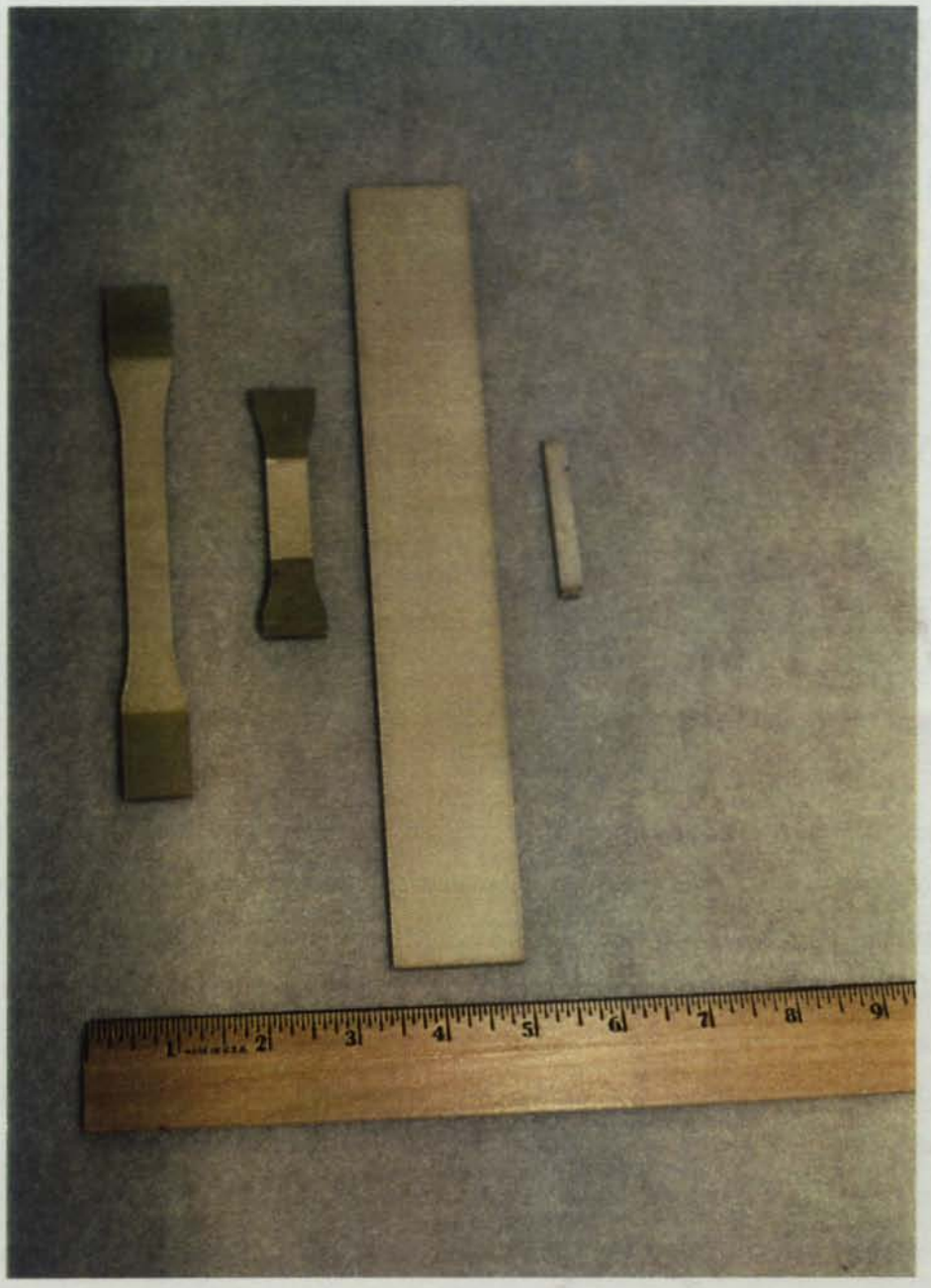

Figure 1. Mechanical Test Specimens From the Polyester Matrix Composite Panels - From Left to Right, Tension Compression, Flexure, and Short Beam Shear.

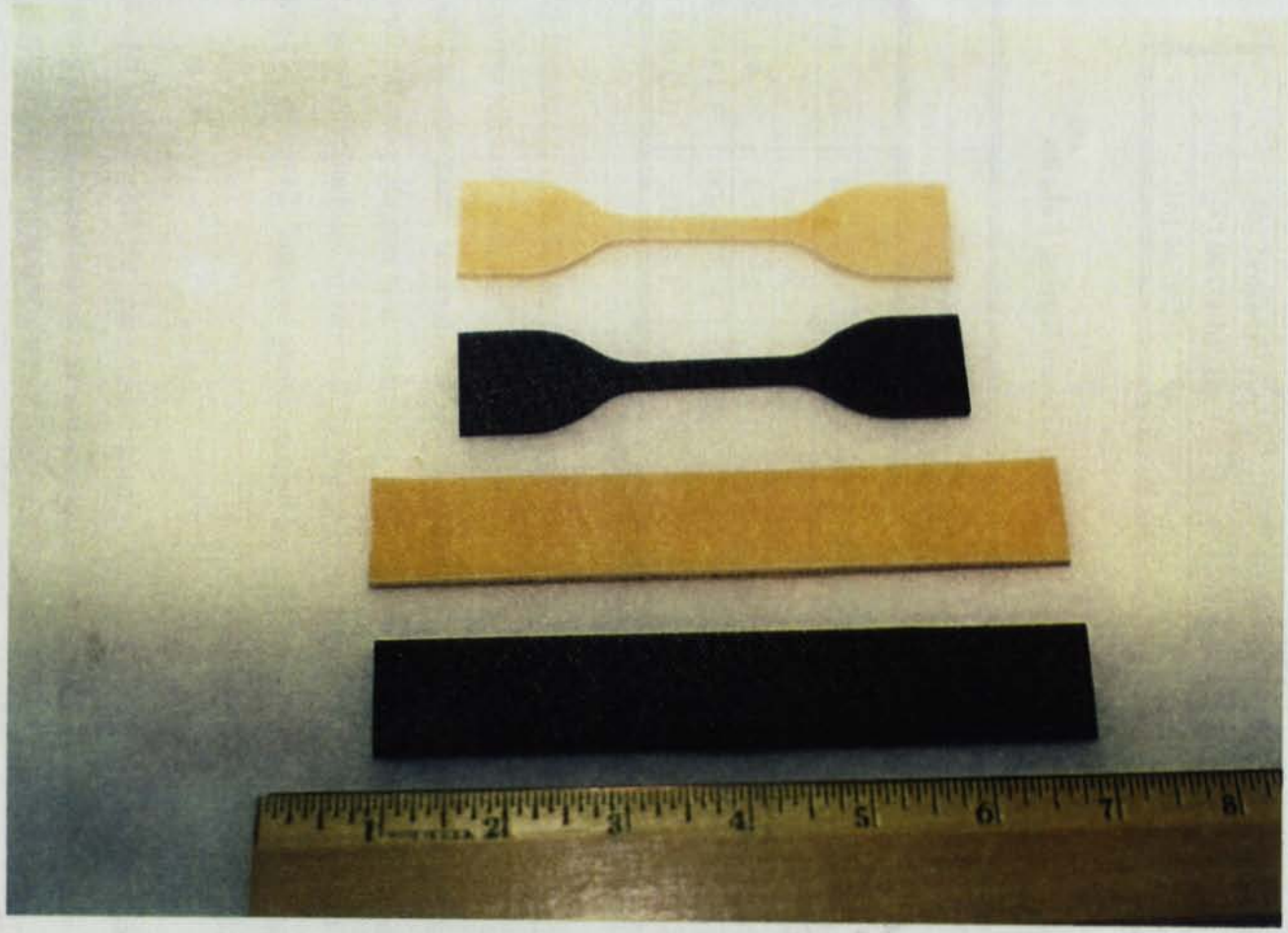

Figure 2. Mechanical Test Specimens From the Polyurethane Matrix Composite Panels - Tension (Left) and Flexure (Right).

Table 1. Required Tests and ASTM Specifications

Test	Specification No.
Tensile Strength and Modulus	ASTM-D638 [5]
Compressive Strength and Modulus	ASTM-D695 [6]
Flexure Strength and Modulus	ASTM-D790 [7]
Short-Beam-Shear Strength	ASTM-D2344 [8]

Table 2. Test Results for Samples From Woven Roving Fabrics

Test Sample No.	1	2	3	4
Type	Uncoated		Coated	
Test Direction (°)	0	90	0	90
Tensile Strength (ksi)	71.6 ±3.7	72.5 ±1.6	58.5 ±4.6	62.7 ±3.9
Tensile Modulus (Msi)	3.3 ±0.2	3.2 ±0.2	2.7 ±0.4	2.7 ±0.2
Flexure Strength (ksi)	33.2 ±1.0	34.0 ±1.3	23.5 ±1.3	26.4 ±1.5
Flexure Modulus (Msi)	3.6 ±0.2	3.5 ±0.04	3.28 ±0.09	3.4 ±0.09
Short-Beam-Shear Strength (ksi)	3.0 ±0.3	2.8 ±0.1	1.6 ±0.5	1.9 ±0.5

It is not surprising that all mechanical properties are at least a little lower in the coated fabric samples, since the bonding of the polypyrrole coating to the sized glass fiber was not optimized. The short-beam-shear strength, which is a measure of the interlaminar shear strength, is the property most affected by the polypyrrole coating, as expected. It is entirely possible that the poor adhesion of the polypyrrole coating is the cause of all the loss in mechanical strength and that the strength of the fibers has not been affected by the coating process. Seven to 10 samples were tested for each of the reported results.

Several composite panels were also prepared by hand lay-up using the finer weave type 6781 S-2 glass fabric. Only the tensile strength and modulus data can be meaningfully compared for these samples, however, because of the variations in glass-fiber concentration. These data are presented in Table 3. The adherence of the polypyrrole coating was much better for these fabrics, according to the supplier.

Table 3. Data for Samples Cut From Composite Panels

Sample	Type	Percent of Glass (±2%)	Tensile Strength (ksi)	Modulus (Msi)
B1X	Coated	38.0	55.9 ±1.4	2.6 ±0.2
B1Y	Coated	37.5	55.7 ±1.5	2.8 ±0.4
B1AX	Coated	40.1	55.5 ±1.0	2.9 ±0.04
B2X	Coated	35.7	54.7 ±1.1	2.5 ±0.06
B2Y	Coated	37.3	55.4 ±0.6	2.8 ±0.2
B2XA	Coated	36.6	51.9 ±1.8	2.7 ±0.3
SW3X	Uncoated	38.7	54.8 ±1.8	2.6 ±0.1
SW3Y	Uncoated	37.3	53.9 ±1.3	2.6 ±0.1

These results indicate that the coating process had very little effect on the tensile strength and modulus of the composites, and by inference on the strength of the glass fibers. A ±7.7% variability of the glass-fiber concentration for these samples was inferred from the thickness of the individual specimens. This is undesirably large, however, and the relative constancy of the results is probably fortuitous. Although the results are highly suggestive, they present only a part of the picture of the effects of the coating on the mechanical properties.

More consistent results for all of the mechanical properties tested were obtained when samples cut from panels made by the VARTM process were tested. The results of these tests are presented in Table 4. The glass concentration in these composites was 45.7 ±1% by volume. These samples were made with fabrics from a lot of polypyrrole-coated fabrics different from those used in the samples in Table 3. The scatter in the data for the different groups of samples is reasonable for these measurements.

The differences in tensile, compressive, and flexure strengths between the polypyrrole-coated samples and the Volan-sized samples are about as large as those between the Volan-sized and amino-silane-sized samples. The values of the tensile and compressive moduli are relatively unchanged, however. The flexure modulus actually increases for the polypyrrole-coated samples. The short-beam-shear strength decreases significantly, however. The results for the

Table 4. Data for Samples Cut From Composite Panels Made by the VARTM Process

Test	Amino-Silane Sizing	Volan Sizing	Polypyrrole Coated
Tensile Strength (ksi)	71.5 ±3.0	58.9 ±2.1	49.2 ±3.1
Tenisle Modulus (Msi)	3.05 ±0.2	3.02 ±0.25	2.95 ±0.23
Flexure Strength (ksi)	84.6 ±1.1	69.6 ±1.6	45.3 ±1.5
Flexure Modulus (Msi)	3.37 ±0.01	3.34 ±0.04	4.44 ±0.06
Compressive Strength (ksi)	33.6 ±2.6	26.2 ±2.0	18.3 ±1.7
Compressive Modulus (Msi)	1.33 ±0.03	1.30 ±0.03	1.34 ±0.04
Short-Beam-Shear Strength (ksi)	4.72 ±0.5	3.86 ±0.04	1.78 ±0.04

flexure, compressive, and short-beam-shear strengths also indicate that the polypyrrole coating has a significant effect on the fiber matrix interface, as might be expected.

It is possible that the fiber matrix interface properties are also the cause of the lower tensile strength of the composites with the polypyrrole-coated fibers and that the strengths of the fibers is not greatly affected by the coating process. The reason why the tensile strength is not as high for these polypyrrole-coated samples as it was for the samples in Table 3 is not clear. The samples came from lots of fabrics made at different times several years apart. The adhesion of the coating was nominally equally good for both lots of coated fabrics, although it might not have been. The data clearly demonstrate that the polypyrrole coating alters the interface properties, but do not indicate whether the fiber strength is also affected.

3.2 Polyurethane-Based Composites. The tensile strength and flexure modulus of composites of the polypyrrole-coated S-2 glass in a Uniroyal Adiprene L-100 matrix resin was also measured. This resin is flexible, rather than brittle, and has a hardness of Shore A-90. Composites of this resin therefore have mechanical properties that differ from polyester-based composites. The interface mechanical properties are also different for the polyurethane resin as a consequence of the different chemical composition of the resin. Test results on samples of these composites are shown in Table 5. The glass concentration in these composites was 41 ±1% by volume.

Table 5. Test Results for Polyurethane Resin Matrix Composite Samples

Test	Uncoated 1	Uncoated 2	120 Ω	3,520 and 530 Ω
Tenisle Strength (ksi)	27.7 ±1.7	26.5 ±2.1	31.0 ±0.8	28.4 ±2.2
Flexure Modulus (Msi)	—	1.32 ±0.05	—	1.30 ±0.04

Surprisingly, the tensile strength of the polypyrrole-coated fabric-based composites was slightly higher than for those made with the uncoated amino-silane-sized fabrics. This strength difference could be due to the mechanical properties of the interface, although there is the possibility that the polypyrrole-coated fibers are stronger. The results are consistent with the postulate that the fibers are not seriously weakened by the coating process. The flexure modulus is essentially the same for the uncoated-fabric and coated-fabric composites.

4. Ballistic Properties

4.1 Pre-1995 Work. In previous unpublished work, a 69-ply composite panel was fabricated in which the first 10 plies were polypyrrole-coated S-2 glass woven roving with a polyester semicompatible sizing (Owens-Corning's type 463). The resin in the first 10 plies was Alpha Owens-Corning's E-701-3 polyester. The balance of the composite was made using S-2 glass roving that had been prepregged with Cytec-Fiberite CYCOM 4102 polyester resin.* This 69-ply panel was tested against a 20-mm fragment-simulating projectile. The V_{50} results were well within the range typical for similar S-2 glass laminates without polypyrrole-coated fabrics. The glass fibers in the first layer of such a composite are simply cut through by this type of projectile. No effect from the polypyrrole coating would be expected, provided that the fibers are not too badly damaged by the coating process. This type of thick S-2 glass polyester resin composite is similar to that used as weight bearing structural armor on the Composite Infantry Fighting Vehicle (CIFV). Although this data point is certainly encouraging, a more definitive test would have to be performed on a thinner laminate with a smaller projectile. No other

* Cytec-Fiberite, 1440 North Kraemer Boulevard, Anaheim, CA 92806.

ballistic tests have previously been reported for composite samples made using polypyrrole-coated S-2 glass fabrics.

4.2 New Work. The samples used in ballistic tests in this work were also prepared using the VARTM process with dry fabrics and Alpha Owens Corning E701-3 polyester resin. A 2-ft × 4-ft laminate of 25 plies of type 6781 S-2 glass fabrics with the JPS amino-silane sizing was fabricated and cut into 1-ft square test samples using a panel saw with a diamond blade. A similar laminate was fabricated using 20 plies of polypyrrole-coated fabrics, with three plies of uncoated fabric at the front and two plies at the rear. As with the mechanical test samples, the polypyrrole-coated fabrics were a random mixture of fabrics with different sheet resistances.

The 1-ft square panels were tested vs. a 22-cal. fragment-simulating projectile per MIL-STD-662 [10]. The V_{50} values for the uncoated and polypyrrole-coated S-2 glass composites were essentially the same, with the polypyrrole-coated composites possibly, but not definitely, just a little higher. The V_{50}, high-partial, and low-complete velocities in feet per second are shown in Table 6.

Table 6. Ballistic Test Results

Velocity	Coated Fabric (ft/s)	Uncoated Fabric (ft/s)
V_{50}	1,520 ±86	1,590 ±46
High-Partial	1,523	1,583
Low-Complete	1,590	1,600

The entrance holes on the uncoated samples were very similar, as expected (see Figures 3 and 4), while the exit holes on the backs of the samples were quite different. The delaminated areas on the polypyrrole-coated glass panels were much less obvious than on the uncoated glass panels and also had an apparently different shape. Percussion tests, however, show that the delaminated area on the polypyrrole-coated glass panel was much larger than it appeared to be, was more or less circular, and was actually larger than that in the uncoated glass panel. The

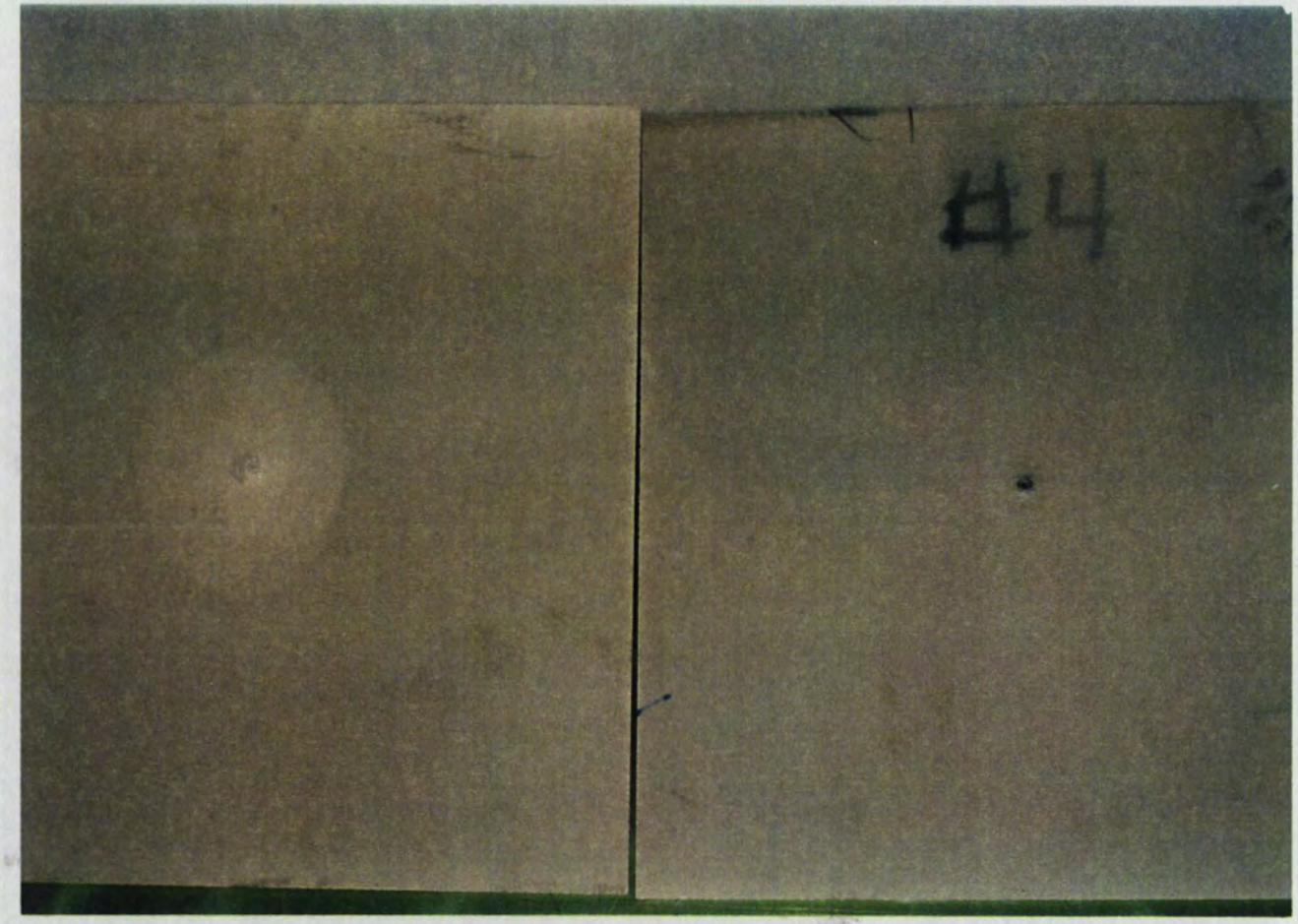

Figure 3. Ballistically Tested Panels From Uncoated Glass Fabric – Back (Left) and Front (Right) Sides.

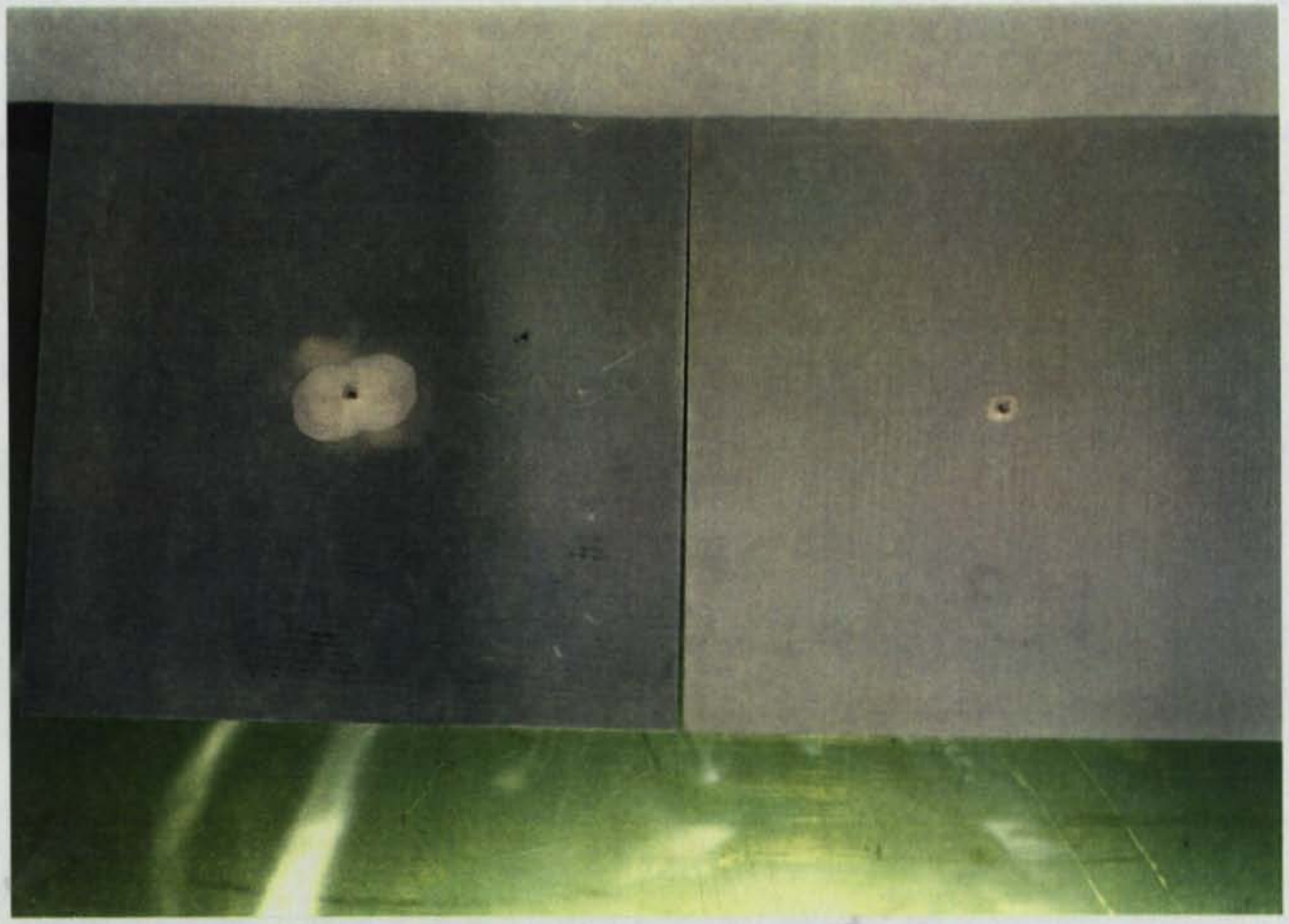

Figure 4. Ballistically Tested Panels From Polypyrrole – Back (Left) and Front (Right) Sides.

apparent delaminated area is marked in black on Figure 5. The percussion test results were verified by direct observation after cutting through two of panels, as shown in Figures 6 and 7.

These ballistic test results are consistent with the postulate that the fibers were not seriously damaged by the polypyrrole-coating process. However, it is impossible to say just how much damage they may have incurred, if any. The lower interlaminar shear strength of the polypyrrole-coated fabric composite improves the ballistic performance a little by increasing the energy lost in delamination. The extra delamination apparently compensates for the lower tensile strength of the composite caused by the changed interface properties. The difference in ballistic strengths is small in any event.

5. Tensile Tests on the Fabrics

In order to try to establish the effect of the polypyrrole coating on the strengths of the fibers, some tensile strength tests were run on samples of the bare fabrics. Samples 8 in long × 3 in wide were cut from a similar roll of uncoated type 6781 fabric and from a roll of fabric that had a 1,200-Ω-per-square coating applied. These samples were held in 1-in-wide rubber-coated jaws and pulled at a rate of 0.1 in/min. Two batches of 30 samples of the uncoated 6781 fabric were tested to identify the problems that could be encountered and to develop technique. The tensile strength of glass fibers is determined by a distribution of minute flaws, which results in a large variation in the apparent fiber strength. Weibull statistics are best used to present the data. This methodology is described in ASTM-C1239-95 [11]. A Weibull plot of the data for one of the batches for the 6781 S-2 glass fabric with the amino-silane sizing is shown in Figure 8. The test data for the other batch are nearly identical. The results are consistent with the proposition that a single flaw population with a distribution of defect sizes determines the strength of the material.

The lines in the Weibull plots represent a fit of the data to the formula

$$P_f = 1 - \exp - (\sigma/\sigma_\Theta)^m,$$

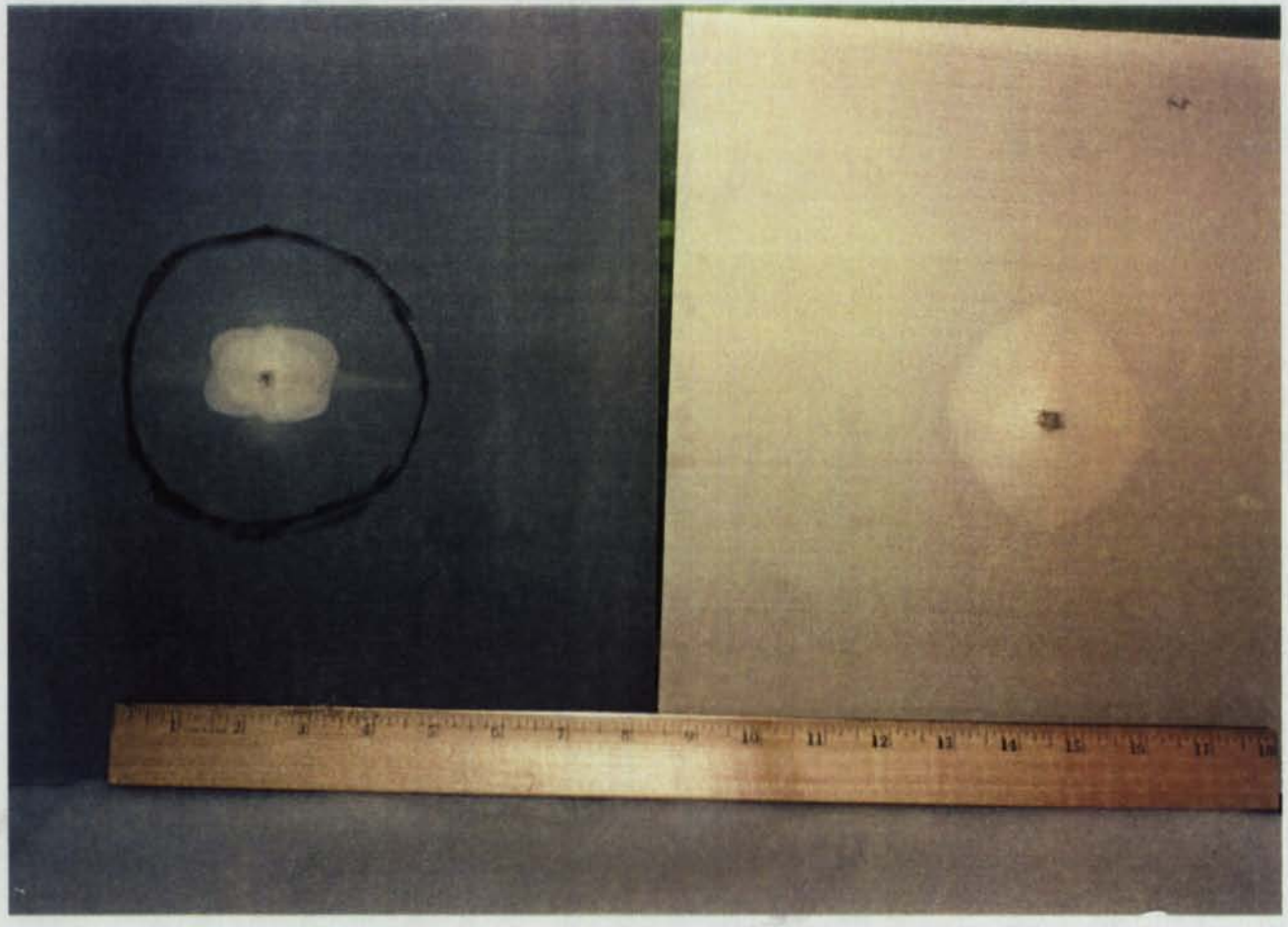

Figure 5. The Delaminated Area on the Coated Glass Panel as Determined by a Simple Percussion Test.

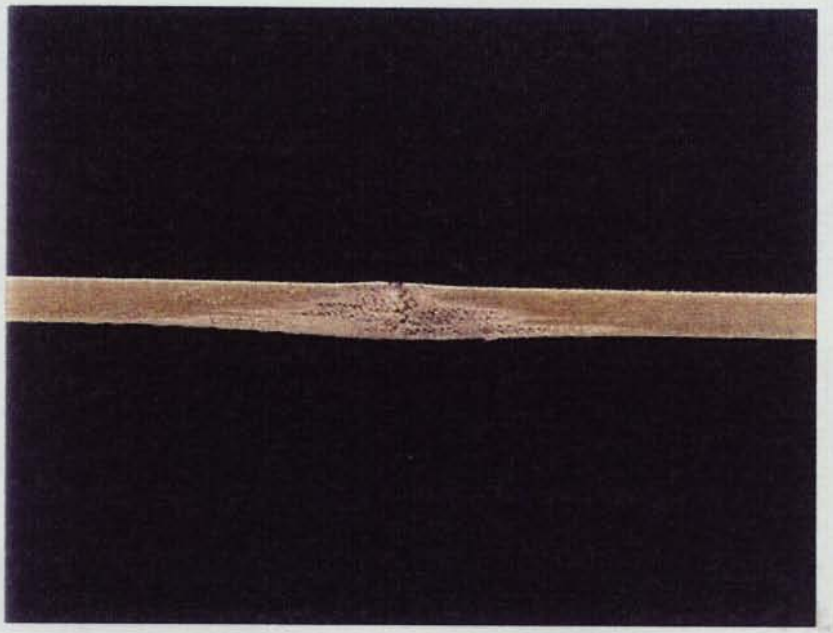

Figure 6. The Delaminated Area in a Ballistically Tested Panel Made From Uncoated Glass, as Seen in a Cut Through the Center of the Sample. About 5 in of the Sample Are Shown.

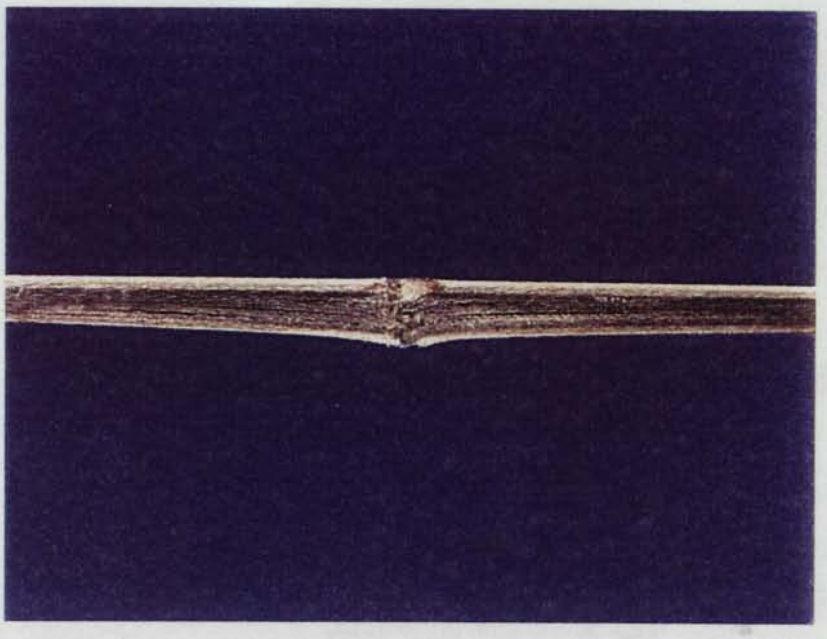

Figure 7. The Delaminated Area in a Ballistically Tested Panel Made From Coated Glass, as Seen in a Cut Through the Center of the Sample. About 5 in of the Sample Are Shown.

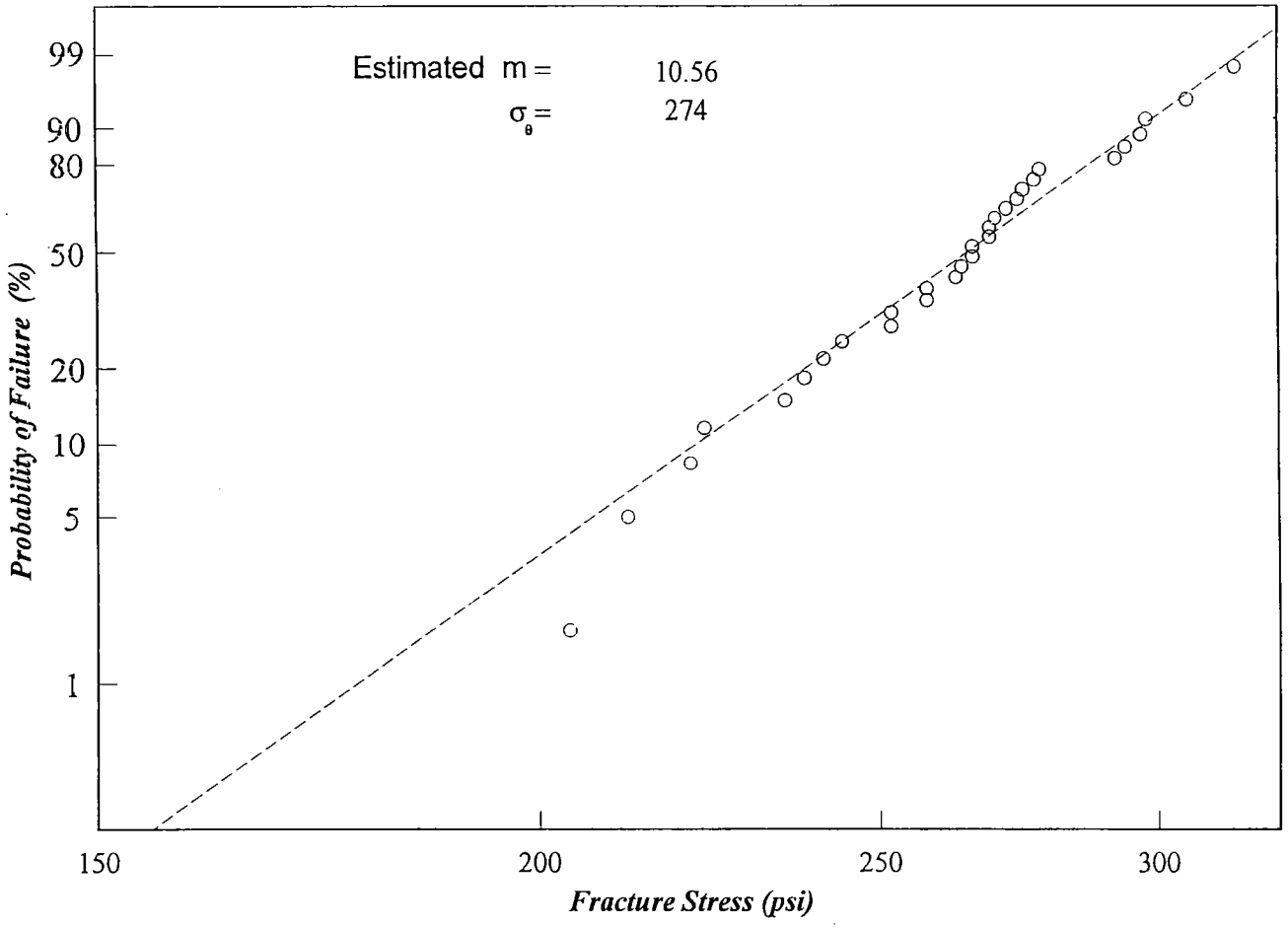

Figure 8. A Weibull Plot for the Tensile Strength of a Batch of Samples of Type 6781 S-2 Glass Fabric With an Amino-Silane Sizing.

where P_f is the probability of failure, σ is the strength (load in this case), σ_Θ is the characteristic strength, and m is an experimentally determined constant. In general, the higher the "m" value, the narrower the distribution of strength-limiting flaws. The characteristic strength (load), σ_Θ, is that at which 63.2% of the samples have failed. Average and Weibull strengths for the samples tested are shown in Table 7.

Table 7. Average and Weibull Strengths

Fabric	Average Strength and Standard Deviation (lb)	Weibull Strength (lb)	Weibull Slope (m)
Amino-Silane 1	262 ±29.9	274	10.6
Amino-Silane 2	263 ±27.5	275	10.5
Volan	212 ±17.3	220	11.2
1,200-Ω Polypyrrole	320 ±29.0	333	13.5

When comparable tests were performed on an S-2 glass fabric that had been coated with polypyrrole, it was immediately obvious that this fabric was stronger. A Weibull plot for the 1,200-Ω-per-square fabric is shown in Figure 9. The reasons for the apparently higher tensile strength are not entirely clear. However, the coated fabrics are somewhat smoother to the touch than the uncoated fabrics, and the most likely explanation for the apparent strength difference is that the coating has increased the lubricity of the fibers. This reduces friction as the fibers rub against each other and makes the fibers less likely to break when the fabric is pulled. It is also possible that the polypyrrole coating simply coats over minute bare spots on the sized fibers. The acid bath treatment could possibly help round out and thus reduce the sharpness of the strength-limiting flaws in the glass, although this seems unlikely since the fabrics are sized.

In order to test the lubricity effect argument, samples of a very stiff type 6781 S-2 glass fabric with a nonlubricious "Volan" sizing were also tested. The test results for samples of this fabric were about 20% lower than for the fabrics with the amino-silane sizing. Figure 10 shows the Weibull plot for the data. The results support the argument that the lubricity is the major source of the difference in the test rests for the different fabrics.

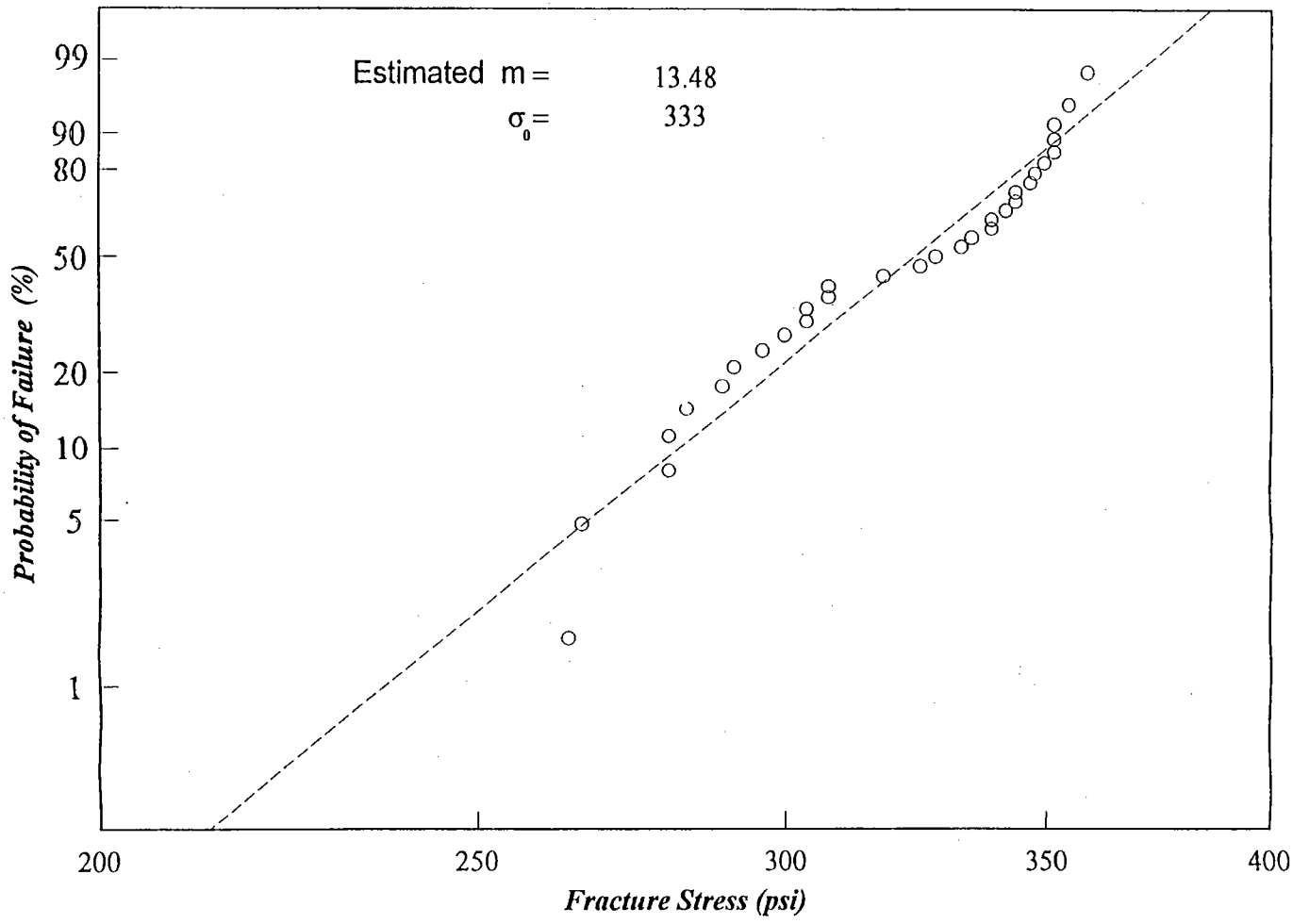

Figure 9. A Weibull Plot for the Tensile Strength of a Batch of Samples of Type 6781 S-2 Glass Fabric With an Amino-Silane Sizing That Had Been Polypyrrole-Coated to Produce a 1,200-Ω-Per-Square-Sheet Resistance.

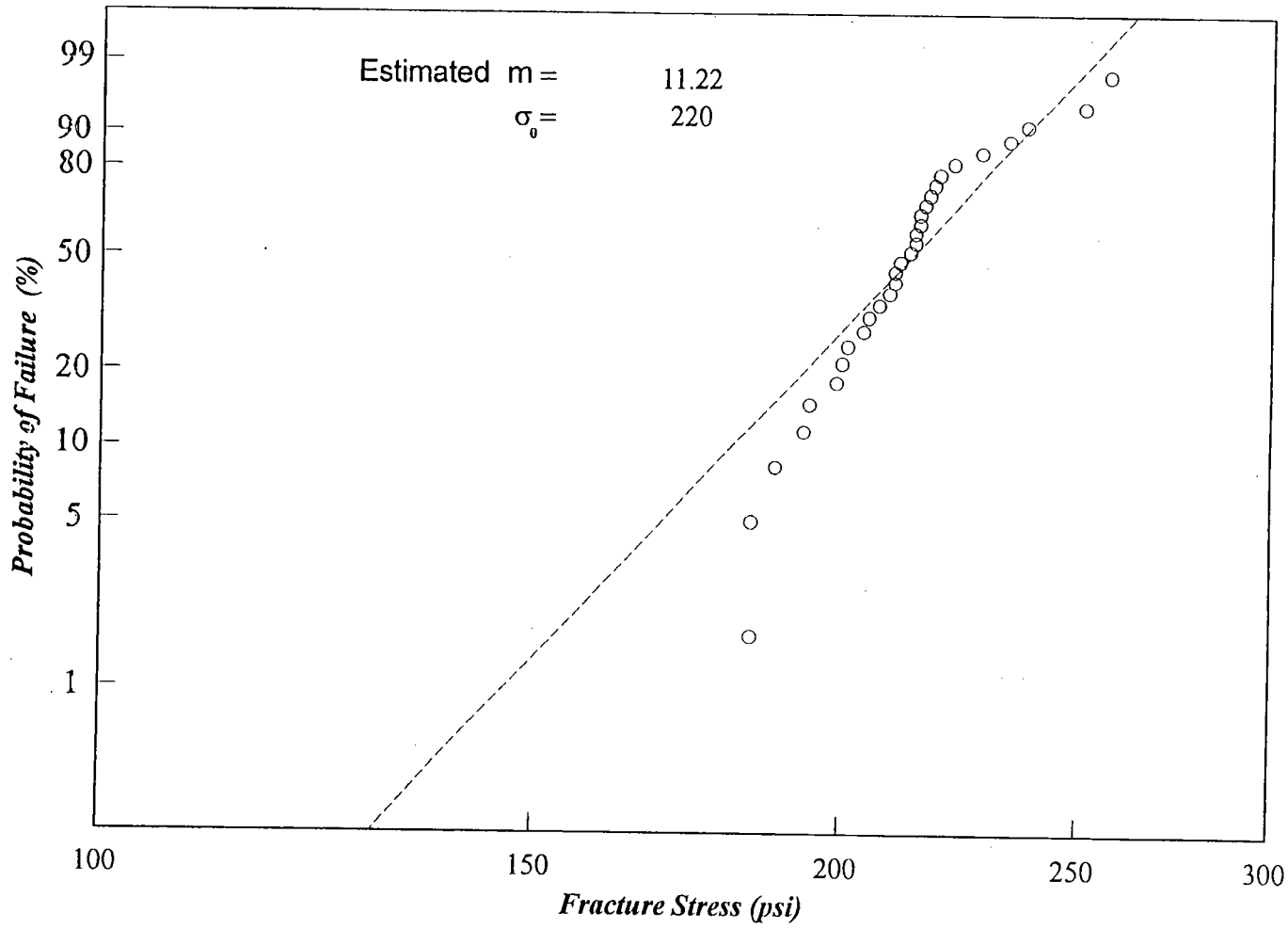

Figure 10. A Weibull Plot for the Tensile Strength of a Batch of Samples of Type 6781 S-2 Glass Fabric With Voaln Sizing.

6. Conclusions

The results of the ballistic and tensile tests on the polyester and tensile tests on the polyurethane resin matrix composites and on the bare fabrics support the proposition that damage to S-2 glass fibers by the polypyrrole-coating process is not large and is very possibly negligible. True proof of this proposition would require direct tests on large samples of single fibers, which would be very difficult and possibly inconclusive in view of the fragility of the single fibers. The interface properties of the fibers in polyester resin matrix composites are significantly affected by the polypyrrole coating, as evidenced by the flexure, compression, and short-beam-shear results. However, these composites should still be strong enough for the applications envisioned for them. The ballistic test results on coated-fabric-based and uncoated-fabric-based polyester resin matrix composites are comparable, although the coated-fabric composites show a larger degree of delamination.

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13. ABSTRACT *(Maximum 200 words)*

This report presents the results of mechanical and ballistic tests on polyester and polyurethane-based composites of polypyrrole-coated S-2 glass fabrics. The fabrics were obtained from the Milliken Research Corporation, Spartanburg, SC. The data support the proposition that the glass fibers are, at most, slightly damaged by the coating process that requires an acidic solution of pH 1. The mechanical properties of the interface between the glass fibers and the matrix resin are weakened by the presence of the polypyrrole coating in the polyester resin composites. As a consequence, the tensile, compressive, flexure, and short-beam-shear strengths are all lower than comparable composites made with uncoated fabrics. The ballistic properties of the polypyrrole-coated-fabric polyester resin composites are as good or perhaps even slightly better, however, as a result of increased delamination. The tensile strengths of the polypyrrole-coated-fabric polyurethane composites were slightly higher than for similar composites made with uncoated fabrics, although the flexural modulus was not changed. The tensile strength of the polypyrrole-coated fabrics was also measured and found to be about 20% higher than comparable amino-silane-sized fabrics, apparently as a consequence of the increased lubricity of the polypyrrole-coated fibers.

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